ISO Images of Starbursts and Active Galaxies

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Abstract. We present some highlights from the mid-infrared (5-16 μm) images of mergers of massive galaxies obtained with the Infrared Space Observatory (ISO). We have observed: 1) ultraluminous infrared nuclei, 2) luminous dust-enshrouded extranuclear starbursts, and 3) active galaxy nuclei (AGNs). In this contribution we discuss the observations of Arp 299, a prototype for very luminous infrared galaxies, the Antennae which is a prototype of mergers, and Centaurus A which is the closest AGN to Earth. From these observations we conclude the following: 1) the most intense starbursts in colliding systems of galaxies and the most massive stars are dust-enshrouded in regions that appear inconspicuous at optical wavelengths, 2) the most intense nuclear infrared sources are a combination of AGN and starburst activity, 3) the hosts of radio loud AGNs that trigger giant double-lobe structures may be symbiotic galaxies composed of barred spirals inside ellipticals.

Keywords: infrared: galaxies – galaxies: nuclei – galaxies: starburst

1. Nuclear Starbursts

The starbursts in nearby ultraluminous galaxies (Sanders & Mirabel 1996) take place primarily in the nuclear regions. Using ISOCAM we have made observations of the mid-infrared emission at 5-16 μm in a sample of 10 very luminous galaxies. At a distance of 42 Mpc, Arp 299 (Mrk 171; NGC 3690/IC 694) is the closest system of this class with a bolometric luminosity of $8{\times}10^{11}L_{\odot}$. The nuclei are still $\sim$5 kpc apart, and it represents a merger in an earlier stage of evolution compared with NGC 6240 and Arp 220, where the nuclei are $\leq$1 kpc apart. The upper panel of Figure 1 (from Hibbard & Yun, private communication) exhibits optical and HI tidal tails 160 kpc in length emerging from the colliding disks. It is striking that the HI tail is spatially displaced from the optical tail. The lower panel shows the 7 μm emission from Gallais et al. (1999). The 7 and 15 μm images reveal that about 90% of the emission from the whole system comes from the two unresolved dust-enshrouded sources A and B1 which have sizes of less than 300 pc in radius and are inconspicuous in the optical. These two regions are strong HCN sources with some indication of rotation in source B1 (Casoli, et al. 1999). Although the studies of Arp 299 at other wavelengths support the hypothesis that A and B1 are nuclear starbursts, the CVF mid-infrared spectrum of B1 exhibits -besides the signatures of

starbursts- a 3-10 μm continuum frequently observed in AGNs (Laurent et al. 1999).

Source A dominates in the far infrared whereas source B in the mid-infrared (Joy, et al. 1989), and it can be concluded that more than 90% of the bolometric luminosity in Arp 299 comes from the two nuclei with sizes $\leq$300pc in radius. Similar results were obtained for ultraluminous infrared galaxies (e.g. The Superantennae, Mirabel et al. 1991), where more than 98% of the mid-infrared emission at 15μm comes from a nuclear region hosting a Seyfert 2 nucleus.

2. Extranuclear Starbursts

One of the new findings with ISO is a very luminous dust-enshrouded extranuclear starburst in the Antennae (NGC 4038/39). In this early merger of two Sc galaxies we found an extranuclear starburst with size $\leq$ 50 pc in radius producing $\sim$15% of the overall 15 μm mid-infrared output. Furthermore, the analyses of the mid-infrared spectra indicate that the most massive stars in this system are formed inside this optically invisible knot.

In Figure 2 is shown in contours the mid-infrared (12-18 μm) image of the Antennae galaxies obtained with ISO (Mirabel et al. 1998), superimposed on the optical image from HST. Below are shown representative spectra of the two nuclei and the brightest mid-infrared knot.

The multiwavelength view of this prototype merging system suggests caution in deriving scenarios of early evolution of galaxies at high redshift using only observations in the narrow rest-frame ultraviolet wavelength range (Mirabel et al. 1998). Although the actual numbers of this type of systems is not large in the local universe, we must keep in mind that there are indications of strong number density evolution as a function of redshift in luminous infrared galaxies (Sanders & Mirabel 1996; Kim & Sanders 1998), that the most intense starbursts are enshrouded in dust, and that no ultraviolet light leaks out from these regions.

Another example of an extra-nuclear starburst is also observed in the prototypical collisional ring galaxy “The Cartwheel” (Charmandaris et al. 1999). In Figure 3 is shown in contours the mid-infrared image in broad band filters LW2(5-8.5μm) and LW3(12-18μm). The mid-IR maps cover the Cartwheel galaxy and the two nearby companions G1 and G2. The intensity of the mid-IR emission from the outer star forming ring of the Cartwheel shows considerable azimuthal variation and peaks at the most active Hα regions of the ring. Interestingly, in

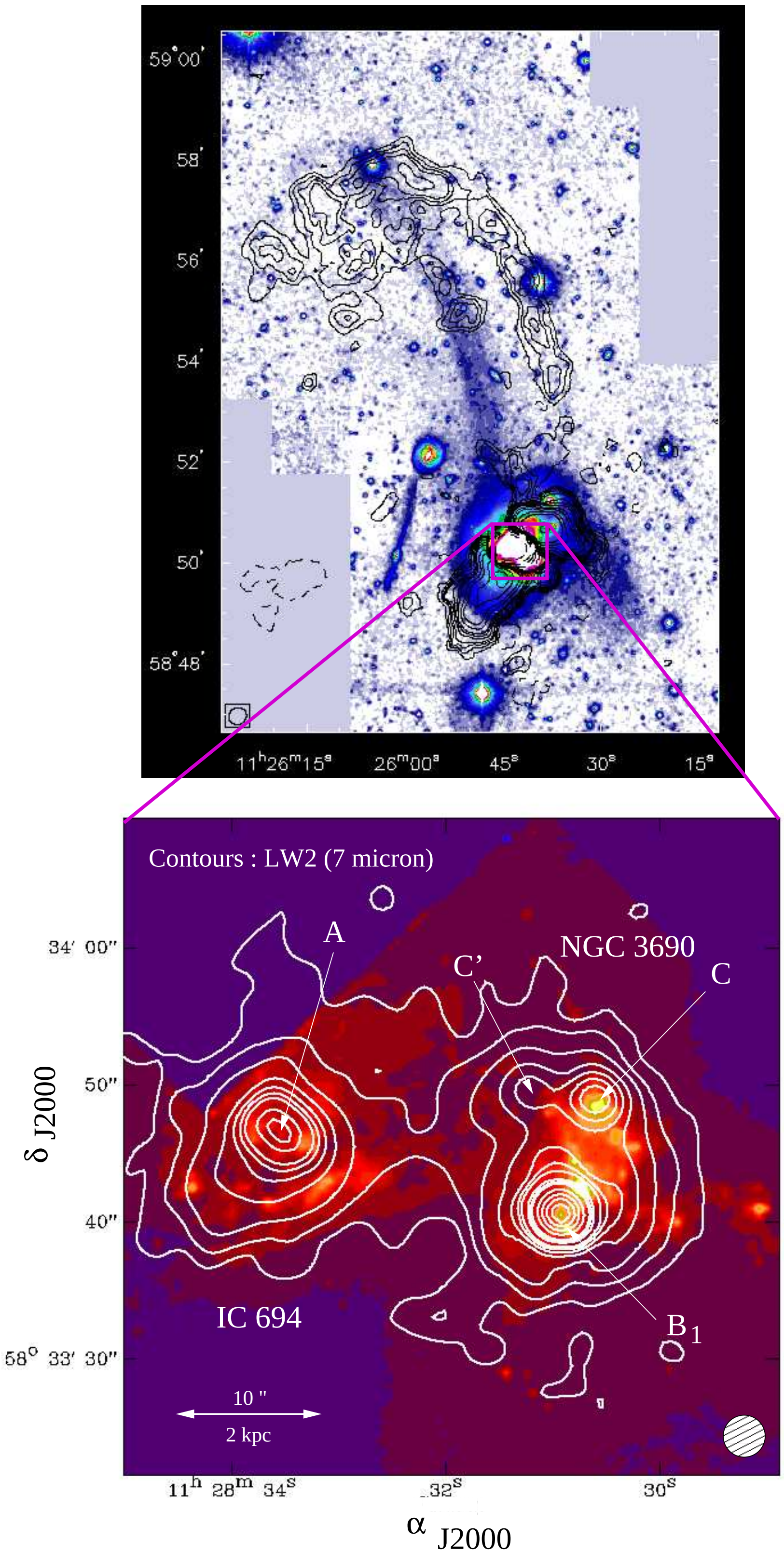

Figure 1. The upper figure shows R band (grey) and HI (contours) images of Arp 299 (Hibbard & Yun, private communication). The 7μm map by Gallais et al. (1999) is shown in the lower panel superposed to the optical HST image. About 90% of the mid-infrared emission comes from the nuclear regions A and B1.

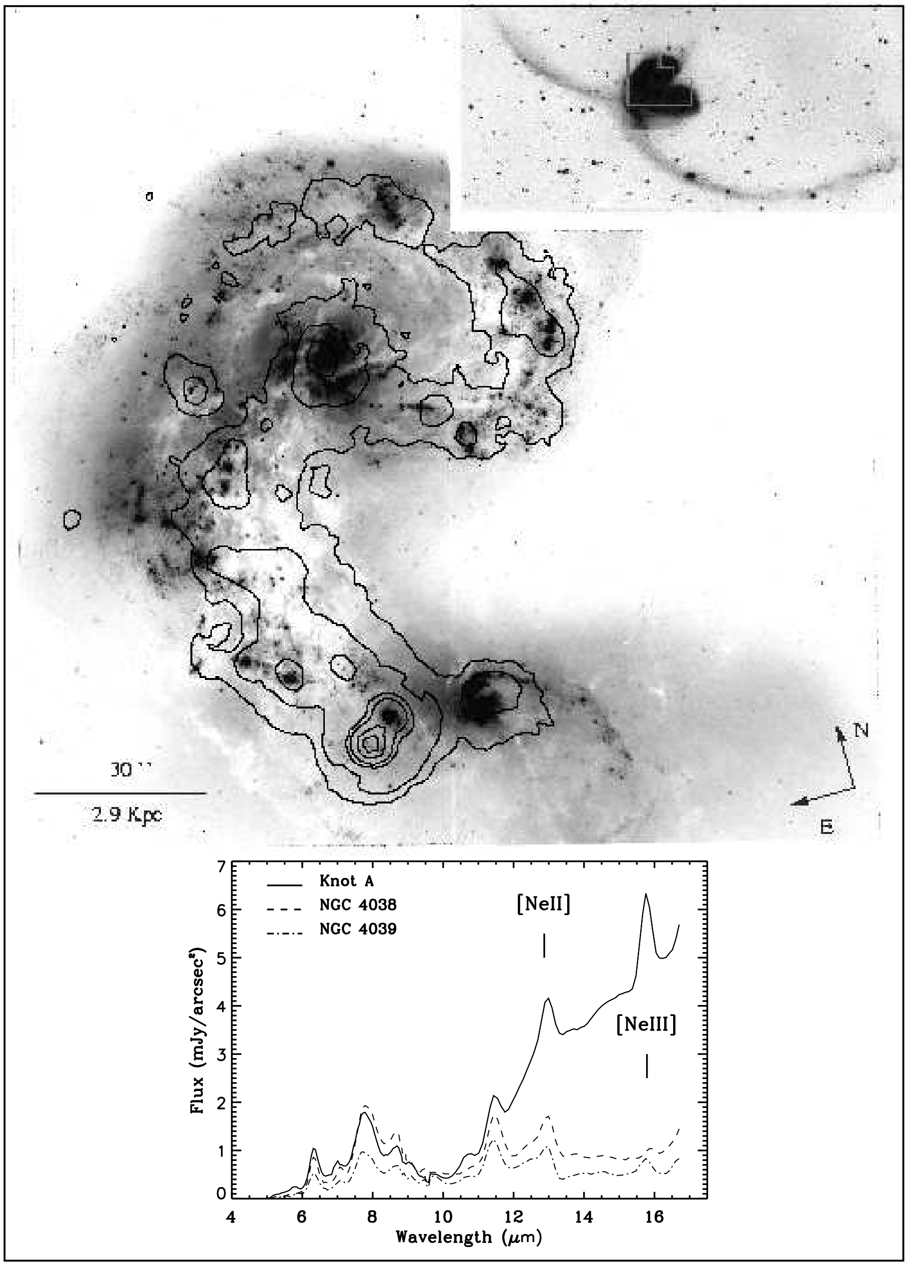

Figure 2. The upper figure from Mirabel et al. (1998) shows a superposition of the mid-infrared (12 -18μm, contours) image of the Antennae galaxies obtained with the Infrared Space Observatory, on the composite optical image with V (5252 Å) and I (8269 Å) filters recovered from the Hubble Space Telescope archive . About half of the mid-infrared emission from the gas and dust that is being heated by recently formed massive stars comes from an off-nuclear region that is clearly displaced from the most prominent dark lanes seen in the optical. The brightest mid-infrared emission comes from a region that is relatively inconspicuous at optical wavelengths. The ISOCAM image was made with a 1.5$''$ pixel field of view. Contours are 0.4, 1, 3, 5, 10, and 15 mJy. The lower figure shows the spectrum of the brightest mid-infrared knot (continuous line) and of the 50 pc radius regions containing the nuclei of NGC 4038 and NGC 4039. The rise of the continuum above 10 μm and strong NeIII line emission observed in the brightest mid-infrared knot indicate that the most massive stars in this system of interacting galaxies are being formed in that optically obscured region, still enshrouded in large quantities of gas and dust.

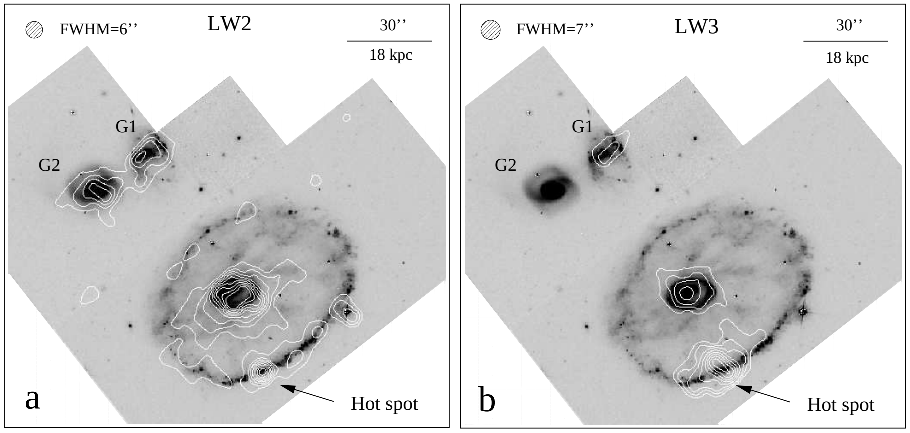

Figure 3. a) Contour map of the ISOCAM LW2 emission overlaid on an HST wide I band image (Charmandaris et al. 1999). The contour levels are from 0.1 to 0.5 mJy/pixel with a step of 0.05 mJy/pixel. b) Contour map of the ISOCAM LW3 emission overlaid on the same HST image. The contour levels are 0.2,0.3,0.4,0.6,0.8,1,1.2 and 1.4 mJy/pixel. North is up and East is left in both images.

the LW3(12-18μm) filter, only the hot-spot is detected in the outer ring. In addition, the LW3/LW2 flux ratio, often used as a diagnostic of the intensity of the radiation field has a value of 5.2 which is comparable to the brightest extranuclear starburst in the Antennae galaxies.

3. AGNs and Symbiotic Galaxies

Giant radio galaxies are thought to be massive ellipticals powered by accretion of interstellar matter onto a supermassive black hole. Interactions with gas rich galaxies may provide the interstellar matter to feed the active galactic nucleus (AGN). To power radio lobes that extend up to distances of hundreds of kiloparsecs, gas has to be funneled from kiloparsec size scales down to the AGN at rates of $\sim$1 $M_\odot$ yr^{-1} during $\sim$10^8 years. Therefore, large and massive quasi-stable structures of gas and dust should exist in the deep interior of the giant elliptical hosts of double lobe radio galaxies. Recent mid-infrared observations with ISO revealed for the first time a bisymmetric spiral structure with the dimensions of a small galaxy at the centre of Centaurus A (Mirabel et al. 1999). The spiral was presumably formed out of the tidal debris of an accreted gas-rich object(s) and has a dust morphology that is remarkably similar to that found in barred spiral galaxies (see Figure 4). The observations of this closest AGN to Earth suggest that the dusty hosts of giant radio galaxies like CenA, are "symbiotic" galaxies composed of a barred spiral inside an elliptical, where the bar serves to funnel gas toward the AGN.

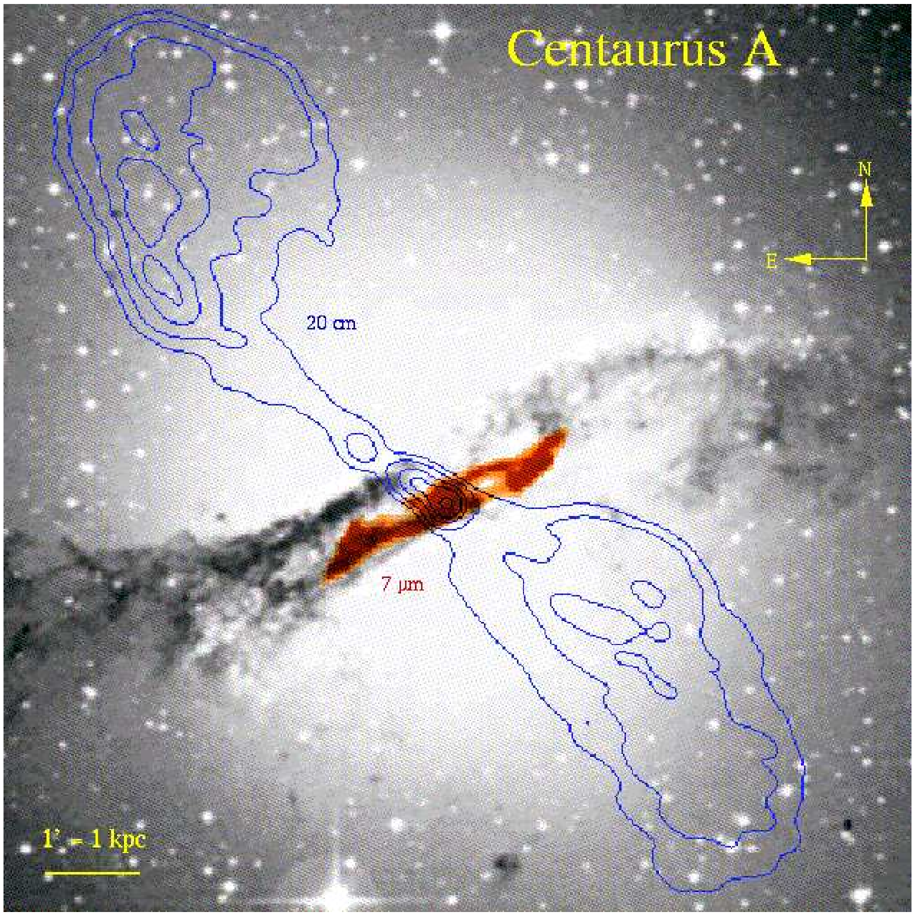

Figure 4. The ISO 7 μm emission (dark structure; Mirabel et al. 1999) and VLA 20 cm continuum in contours (Condon et al. 1996), overlaid on an optical image from the Palomar Digital Sky Survey. The 7 μm emission from dust with a bisymmetric morphology at the centre is about 10 times smaller than the overall size of the shell structure in the elliptical and lies on a plane that is almost parallel to the minor axis of its giant host. Whereas the gas associated with the spiral rotates with a maximum radial velocity of 250 km s^{-1}, the ellipsoidal stellar component rotates slowly approximately perpendicular to the dust lane (Wilkinson et al. 1986). The synchrotron radio jets shown in this figure correspond to the inner structure of a double lobe radio source that extends up to 5° ($\sim$ 300 kpc) on the sky. The jets are believed to be powered by a massive black hole located at the common dynamic center of the elliptical and spiral structures.

The barred spiral at the centre of CenA has dimensions comparable to that of the small Local Group galaxy Messier 33. It lies on a plane that is almost parallel to the minor axis of the giant elliptical. Whereas the spiral rotates with maximum radial velocities of ~ 250 km s^{-1}, the ellipsoidal stellar component seems to rotate slowly (maximum line-of-sight velocity is ~ 40 km s^{-1}) approximately perpendicular to the dust lane. The genesis, morphology, and dynamics of the spiral formed at the centre of CenA are determined by the gravitational potential of the elliptical, much as a usual spiral with its dark matter halo. On the other hand, the AGN that powers the radio jets is fed by gas funneled to the center via the bar structure of the spiral. The spatial co-existence and intimate association between these two distinct and dissimilar systems suggest that Cen A is the result from a cosmic symbiosis.

Acknowledgements

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